Snowmass 2021-Energy Frontier Workshop

July 21, 2020

Electroweak Physics

Open Questions and New Ideas

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European Strategy Update results

The starting point for the Snowmass studies

European Strategy Update 2020

European Strategy for Particle Physics: the cornerstone of Europe's decision-making process for the long-term future of the field

Guide through the statements

2 statements on **Major developments from the 2013 Strategy**
a) Focus on successful completion of HL-LHC upgrade remains a priority
b) Continued support for long-baseline experiments in Japan and US and the Neutrino Platform

3 statements on **General considerations for the 2020 update**
a) Preserve the leading role of CERN for success of European PP community
b) Strengthen the European PP ecosystem of research centres
c) Acknowledge the global nature of PP research

2 statements on **High-priority future initiatives**
a) Higgs factory as the highest-priority next collider and investigation of the technical and financial feasibility of a future hadron collider at CERN
b) Vigorous R&D on innovative accelerator technologies

Letters for itemizing the statements are introduced for identification, do not imply prioritization

4 statements on **Other essential scientific activities**
a) Support for high-impact, financially implementable, experimental initiatives world-wide
b) Acknowledge the essential role of theory
c) Support for instrumentation R&D
d) Support for computing and software infrastructure

2 statements on **Synergies with neighbouring fields**
a) Nuclear physics – cooperation with NuPECC

However, no consensus on the type of Higgs factory (Circular or Linear)

b) Relations with European Commission
c) Open science

4 statements on **Environmental and societal impact**
a) Mitigate environmental impact of particle physics
b) Investment in next generation of researchers
c) Knowledge and technology transfer
d) Cultural heritage: public engagement, education and communication

H. Abramowicz's talk at the CERN council meeting of June 19, 2020
See also F. Giannotti's talk on June 29, 2020 for further remarks

European Strategy Update 2020

- Decisions based on the results of the studies of the different Working Groups formed to assist the Physics Preparatory Group (PPG) in evaluating the physics potential of the different future experiments.

- The Higgs@Future Colliders WG was formed by RECFA for this purpose, to help in areas related to Higgs/EW physics. The main outcome of the WG studies is collected in the report in **JHEP 01 (2020) 139 (1905.03764 [hep-ph])** and summarized in the *Electroweak Physics* chapter of the **Physics Briefing Book**

Higgs Boson studies at future particle colliders

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arXiv:1905.03764v2 [hep-ph] 25 Sep 2019

ABSTRACT

This document aims to provide an assessment of the potential of future colliding beam facilities to perform Higgs boson studies. The analysis builds on the submissions made by the proponents of future colliders to the European Strategy Update process, and takes as its point of departure the results expected at the completion of the HL-LHC program. This report presents quantitative results on many aspects of Higgs physics for future collider projects of sufficient maturity using uniform methodologies. A first version of this report was prepared for the purposes of discussion at the Open Symposium in Granada (13-16/05/2019). Comments and feedback received led to the consideration of additional run scenarios as well as a refined analysis of the impact of electroweak measurements on the Higgs coupling extraction.

CERN-ESU-004
30 September 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

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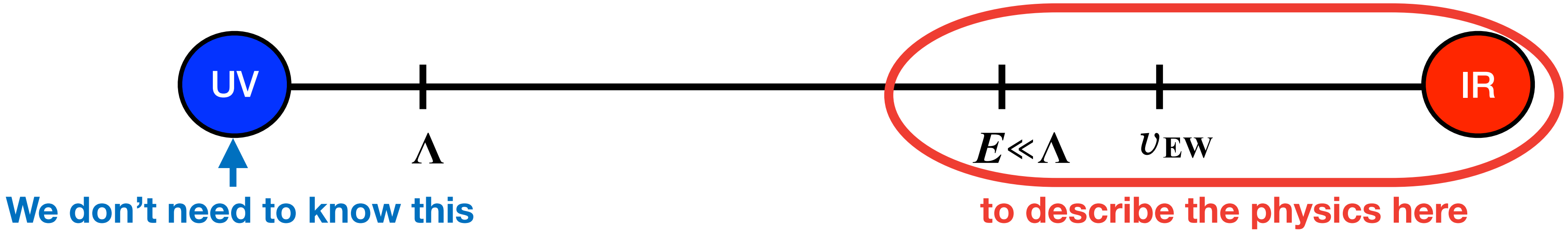
European Strategy Update

European Strategy Update 2020

- For the purpose of this talk and the Snowmass 2021 activities, the relevant part of these results are those related to the SMEFT studies



$$\mathcal{L}_{\mathrm{UV}}(?) \xrightarrow[E \ll \Lambda]{} \mathcal{L}_{\mathrm{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \xrightarrow[\text{suppressed by}]{\text{Effects}} \left(\frac{q}{\Lambda}\right)^{d-4}_{q=v,\,E<\Lambda}$$

- SMEFT $\Rightarrow$ General description of BSM deformations compatible with assumptions:
  - ✓ Heavy new physics + decoupling
  - ✓ SM particles and symmetries at low energies. Assume Higgs belongs to a $SU(2)_L$ doublet H (+ analytic in H=0)
  - ✓ Power counting: operator expansion in canonical mass dimension
- Higgs prospects also studied within the κ framework (not shown in this talk)

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European Strategy Update 2020

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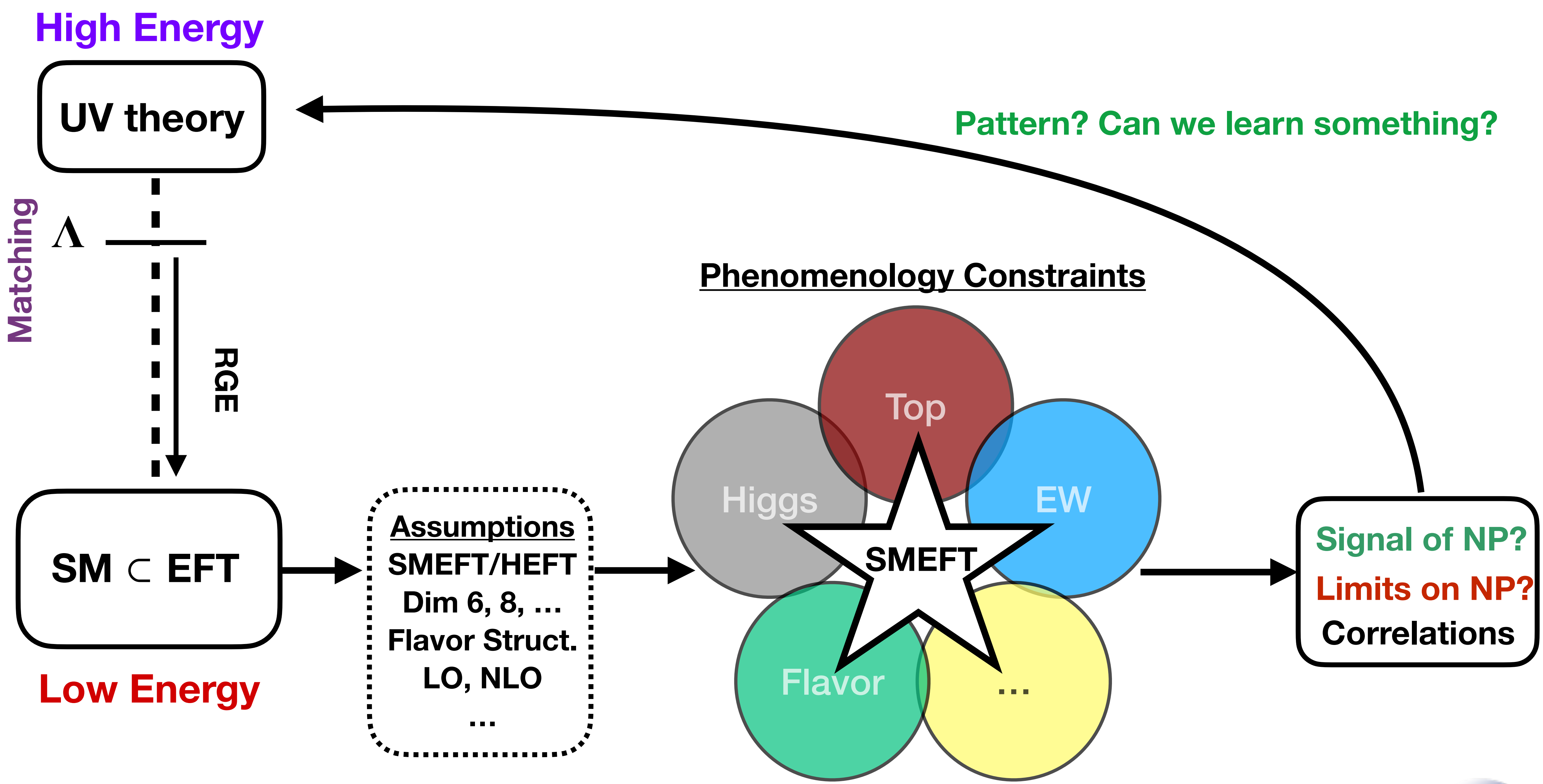

European Strategy Update 2020

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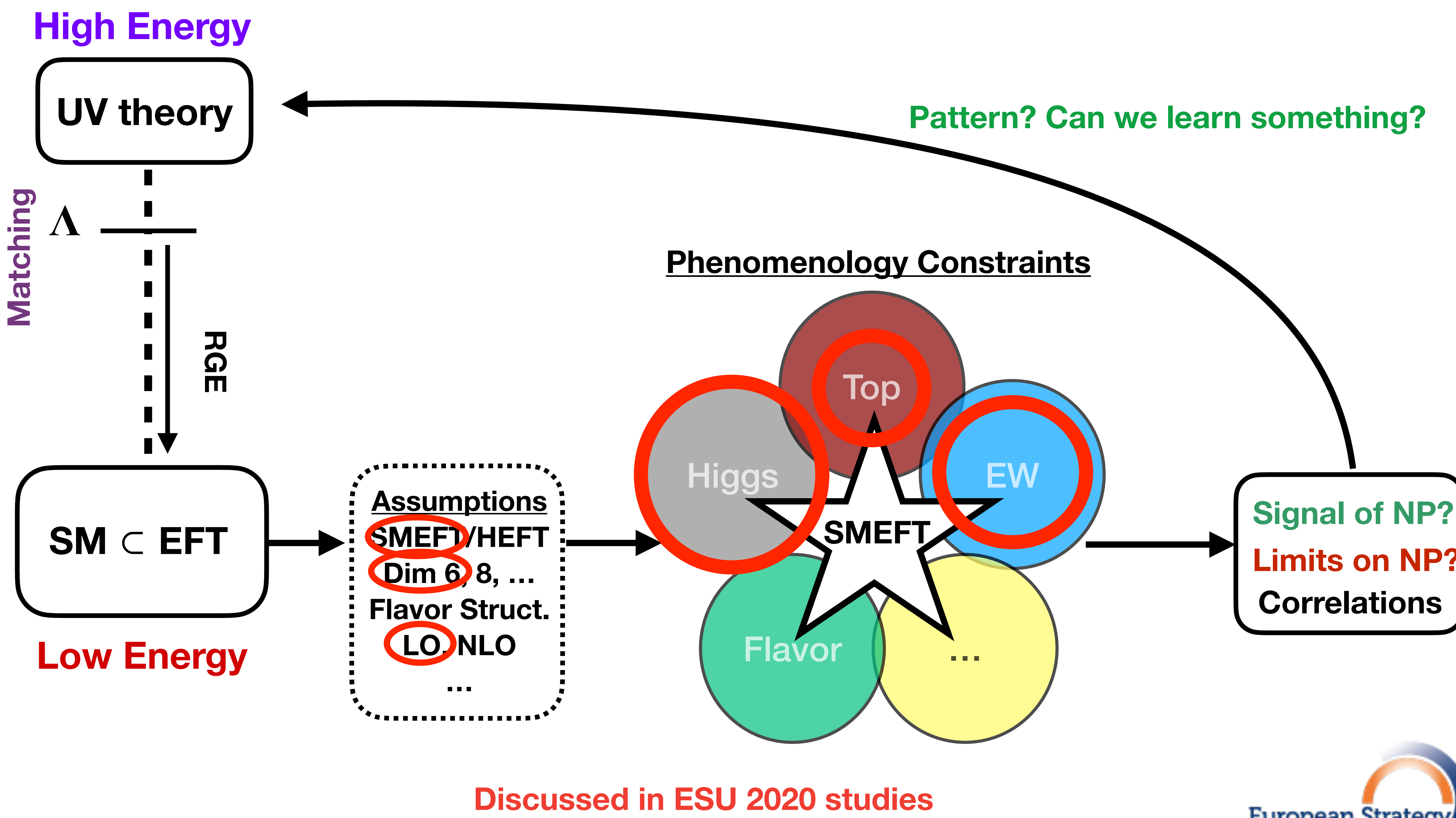
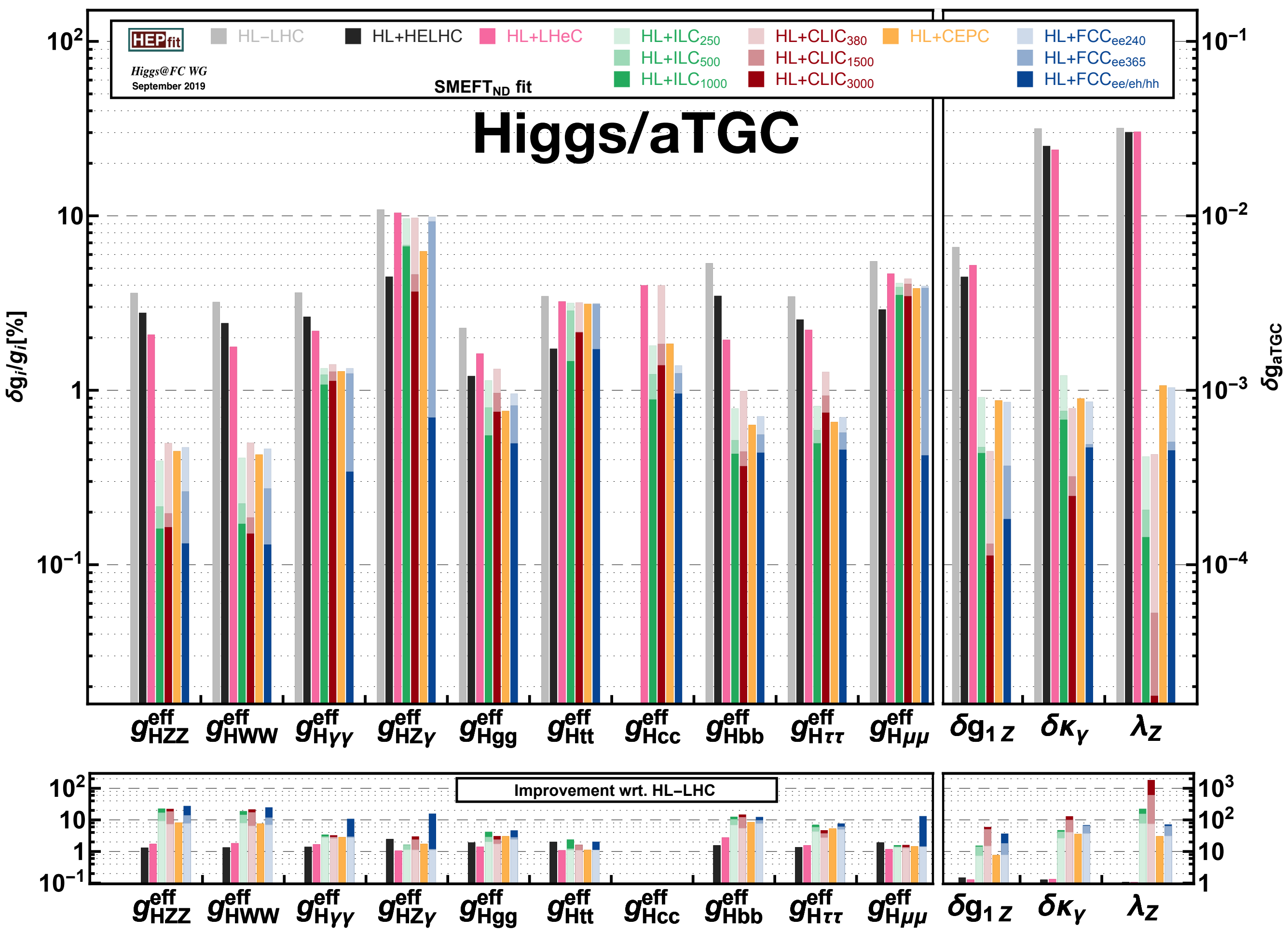
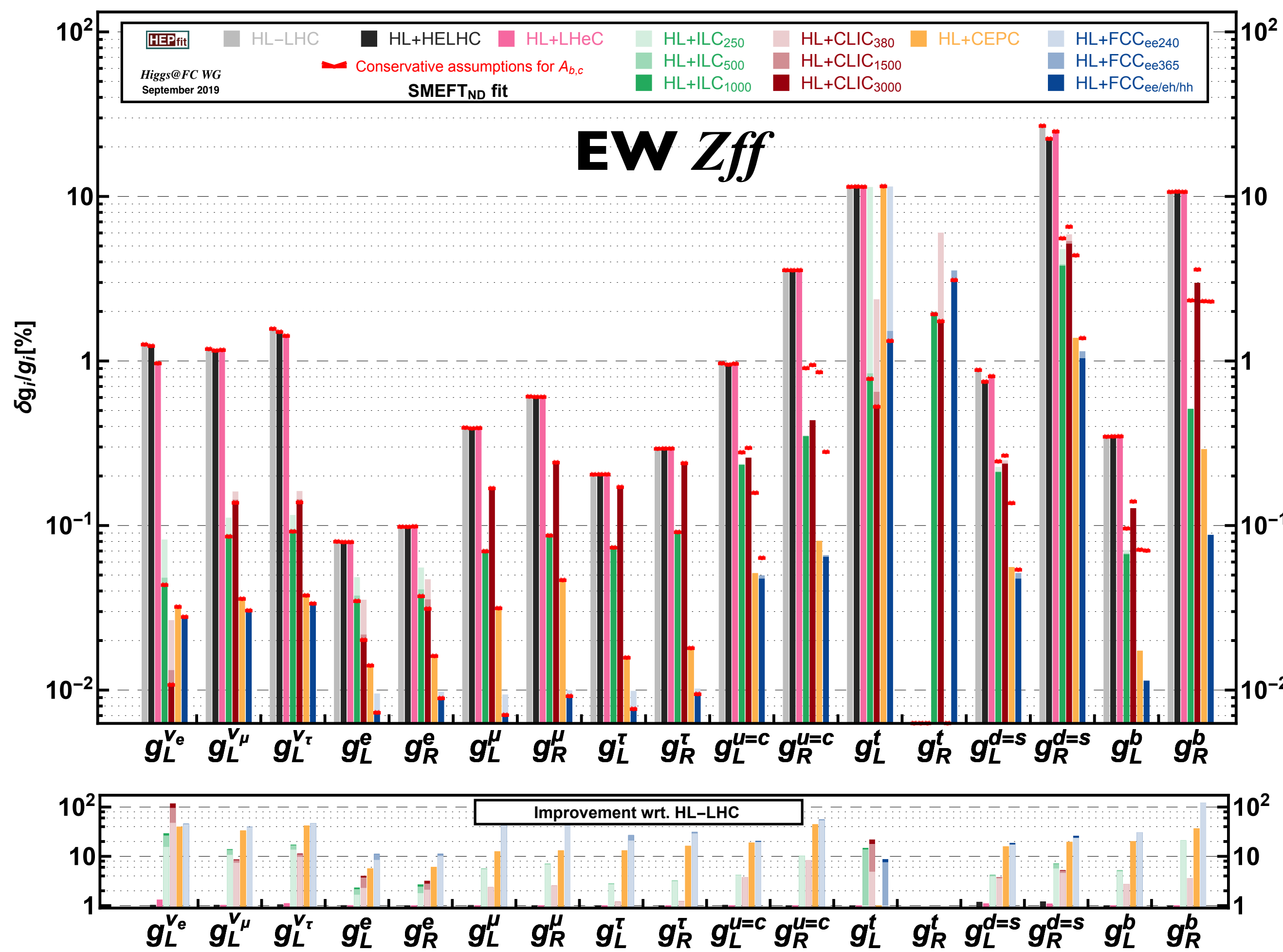


European Strategy Update 2020

Snapshot of available results

EW/Higgs and their interplay studied within SMEFT framework





- Dimension 6 SMEFT fit to Higgs + EW (EWPO and aTGC) + Top (Ztt)
- Results projected into "effective couplings" for comparison of collider capabilities:

$$g_{HX}^{\mathrm{eff}\ 2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\mathrm{SM}}} \qquad \Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w\cos^2\theta_w}(|g_L^e|^2 + |g_R^e|^2), \qquad A_e = \frac{|g_L^e|^2 - |g_R^e|^2}{|g_L^e|^2 + |g_R^e|^2}$$

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European Strategy Update 2020

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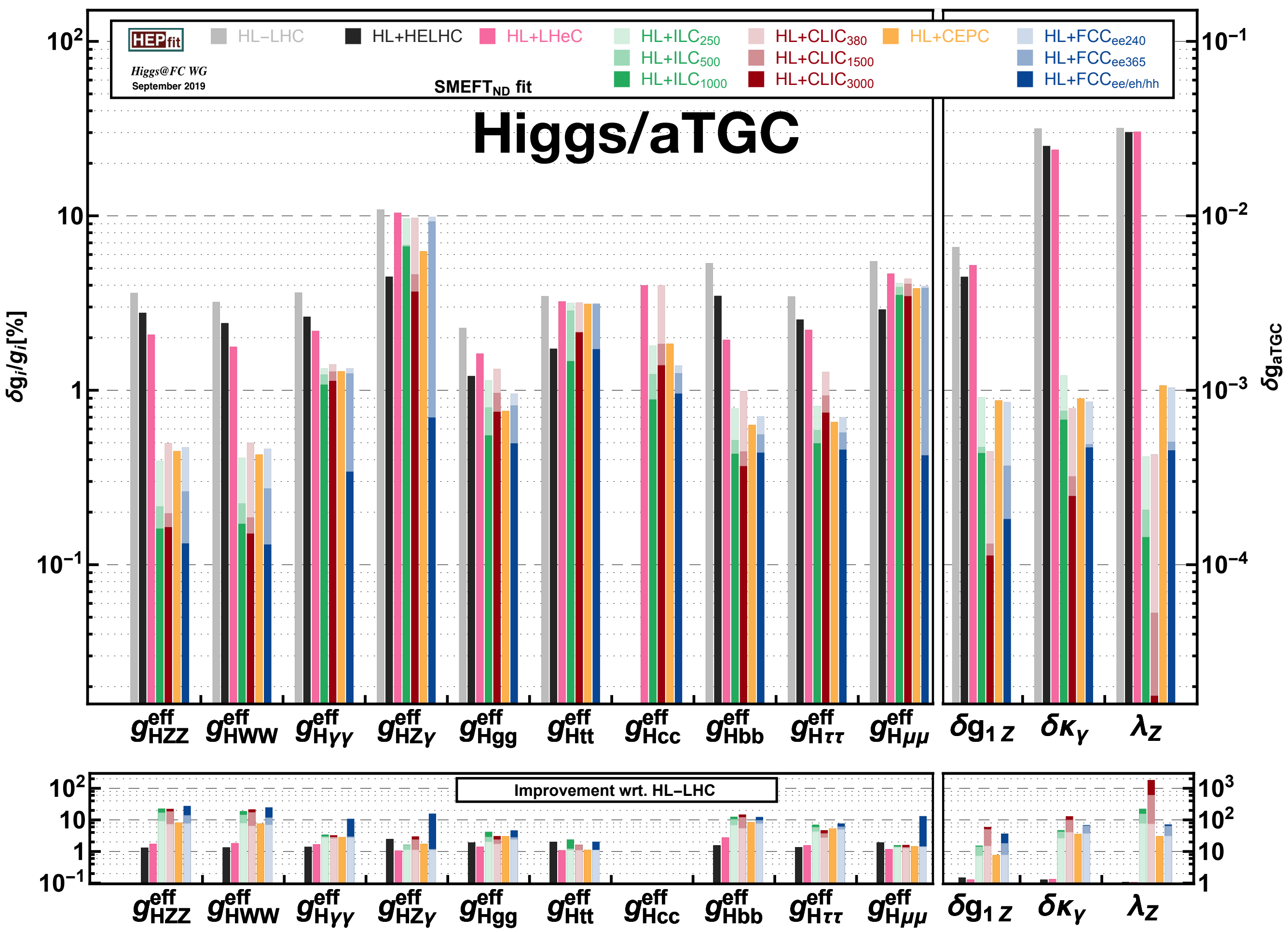
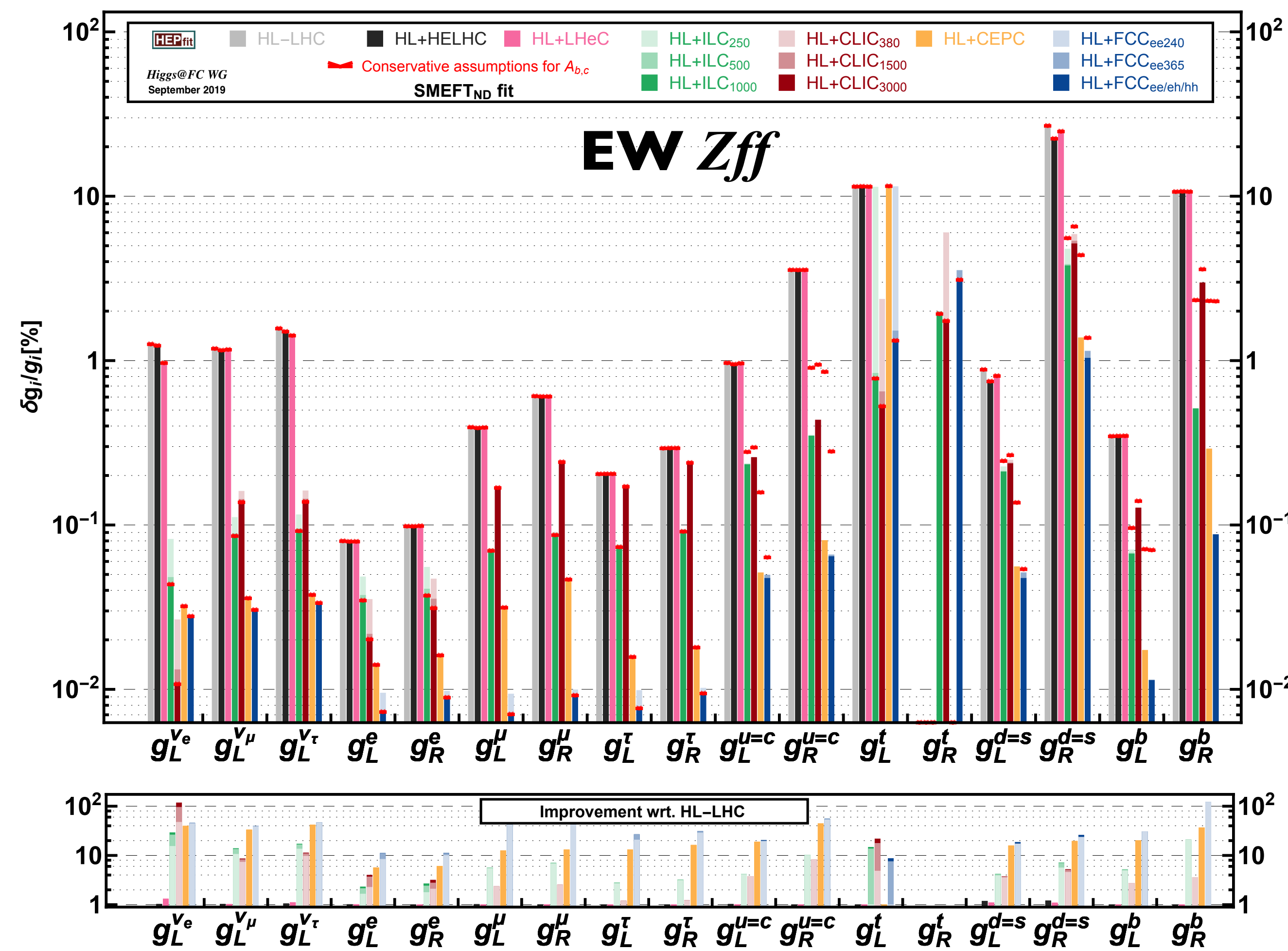




- For more details on these studies see C. Grojean's talk on EF01 kickoff meeting on May 13, 2020, or my own on the EF04 meeting on June 4, 2020
- Results also available for SILH-like EFT (not shown in this talk)

Snowmass 2021

Some relevant topics/studies post ESU 2020

Important topics not covered in ESU studies

Some topics related to EW physics

- **EW precision observables:**
  - √ Detailed assessment of impact of SM uncertainties for EWPO in SMEFT fits.
  - √ Clarify systematics for heavy flavor observables (A_q, R_q).
  - √ Exploit EW measurements outside the Z-pole (low and high energy): requires adding 4-fermion operators into the global fit.
  - √ Flavor (and CP violation): not explored in the ESU SMEFT fits.
- **Multi-boson processes:**
  - √ Full EFT studies of $e^+e^- \to W^+W^-$. Use of "optimal" observables.
  - √ High-E probes of EFT effects that grow with the energy.
  - √ Vector boson scattering: not included in ESU studies.
- **Interplay EW/Higgs/Top:** Top sector only explored superficially:
  - √ Consider effects from 4-fermion operators or top dipole operators.
  - √ Exploit NLO effects of Top couplings in H/EW.
- **SMEFT assumptions:**
  - √ Impact of SMEFT uncertainties: NLO, (dim-6)^2 vs. dim 8, …
  - √ Non-universality: combine with flavor data to explore more flavor BSM scenarios

EW Physics at Snowmass 2021

Electroweak precision observables

Electroweak precision observables in the SM

- Impact of SM theory uncertainties of SM calculations of EWPO:

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
ΔM_Z[MeV]	2.1	–	0.1			
$\Delta\Gamma_Z$[MeV]	2.3	1	0.1	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta \sin^2\theta^\ell_{\rm eff}[10^{-5}]$	23	1.3	0.6	4.5	$\alpha^3, \alpha^2\alpha_s$	1.5
$\Delta R_b[10^{-5}]$	66	14	6	11	$\alpha^3, \alpha^2\alpha_s$	5
$\Delta R_\ell[10^{-3}]$	25	3	1	6	$\alpha^3, \alpha^2\alpha_s$	1.5

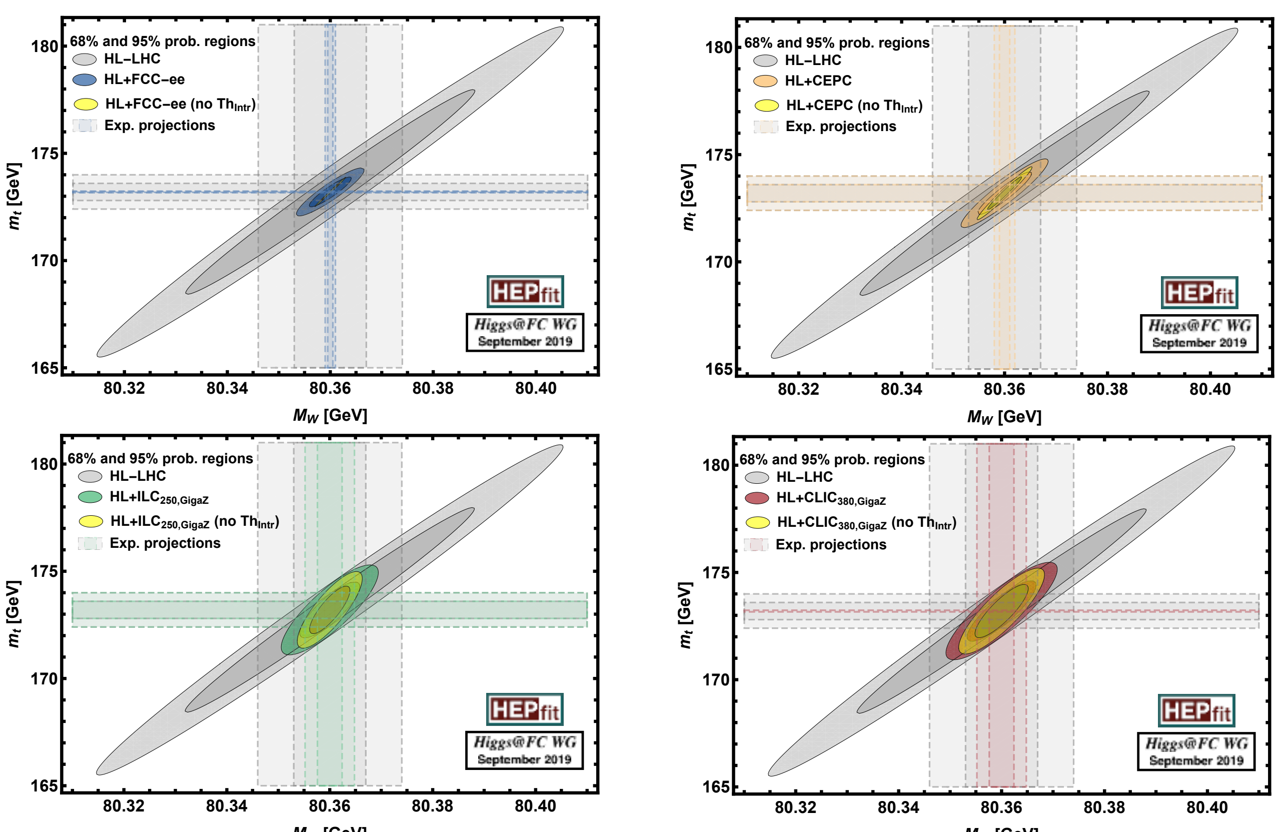
A. Freitas et al., arXiv: 1906.05379 [hep-ph]

Current: Full 2-loop corrections
(Not enough for future Exp. precision)
⇩
Prospects: Extrapolation assuming EW & QCD 3-loop corrections are known

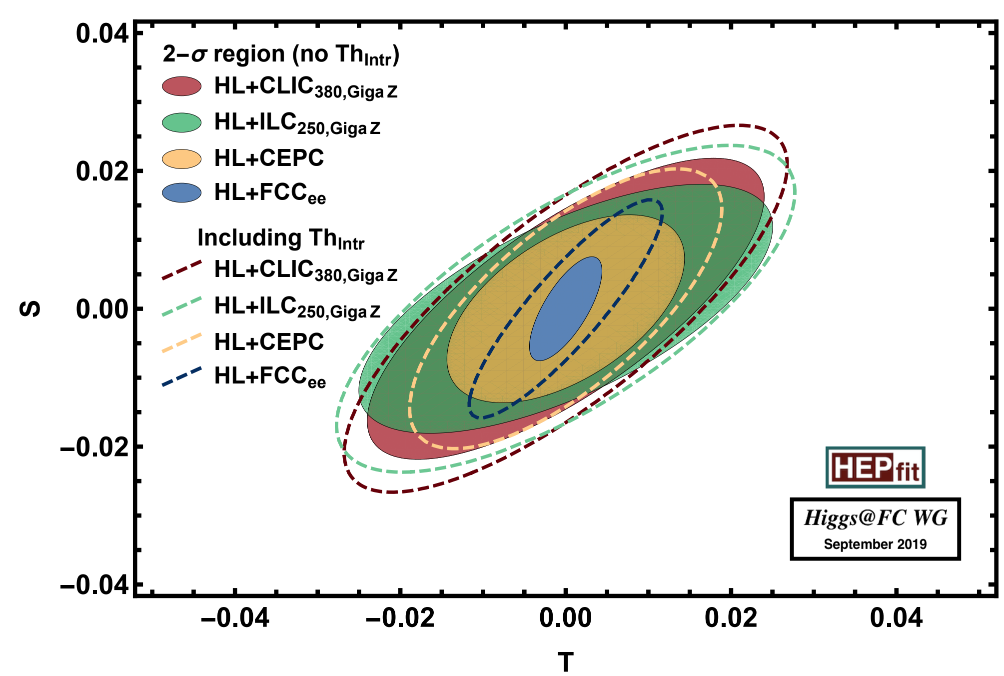
Technically challenging but feasible

Only briefly explored in ESU studies: Future projections still a limiting factor

SM: M_W vs. m_t



BSM: Oblique parameters



Need to study the impact on all directions in the SMEFT fits

Electroweak precision observables in the SM

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(Not enough for future Exp. precision)
⇩
Prospects: Extrapolation assuming EW & QCD 3-loop corrections are known

sible

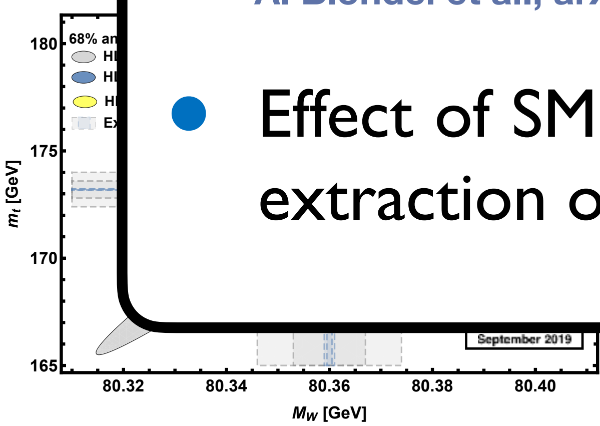
SM uncertainties on WW production?

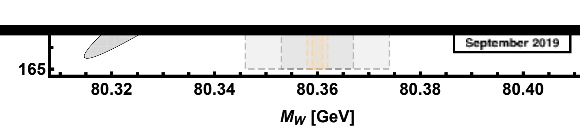
- Studied at threshold (relevant for W mass measurement):

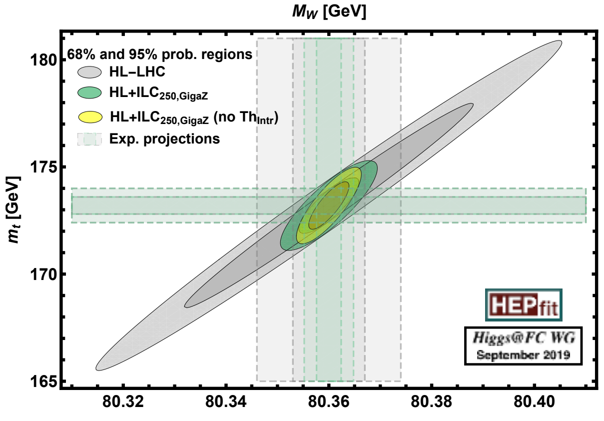
$$\Delta\sigma_{\mathrm{NNLO}} \approx 0.1\% \times \sigma_{\mathrm{Born}} \qquad \Delta\sigma_{\mathrm{N^3LO}} \approx \text{few} \times 0.01\% \times \sigma_{\mathrm{Born}} \quad \rightarrow \quad \Delta M_W = (0.15 - 0.45)\ \mathrm{MeV}$$

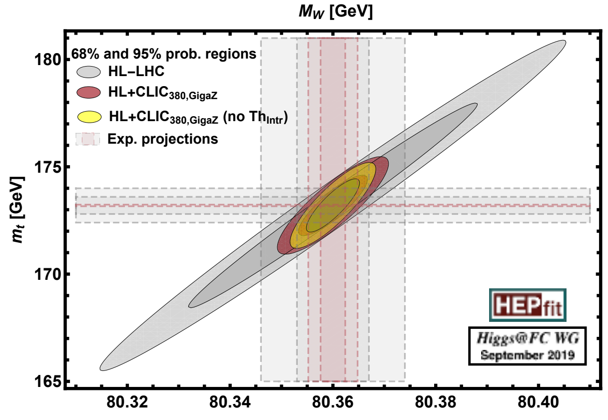
A. Blondel et al., arXiv: 1905.05078 [hep-ph]

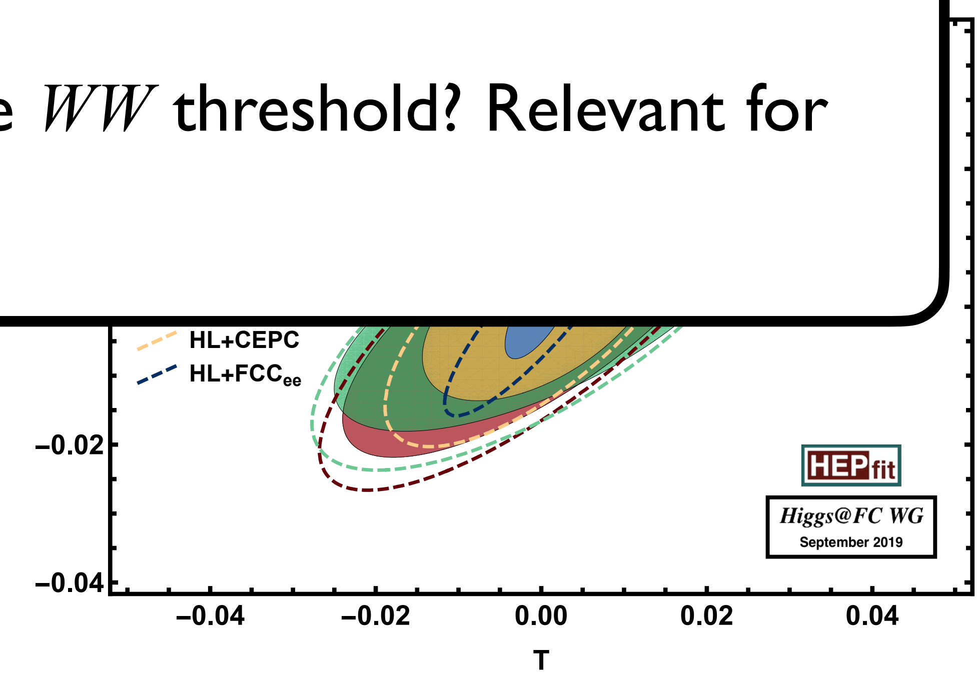
- Effect of SM uncertainty in $e^+e^- \to 4f$ above WW threshold? Relevant for extraction of, e.g., aTGC







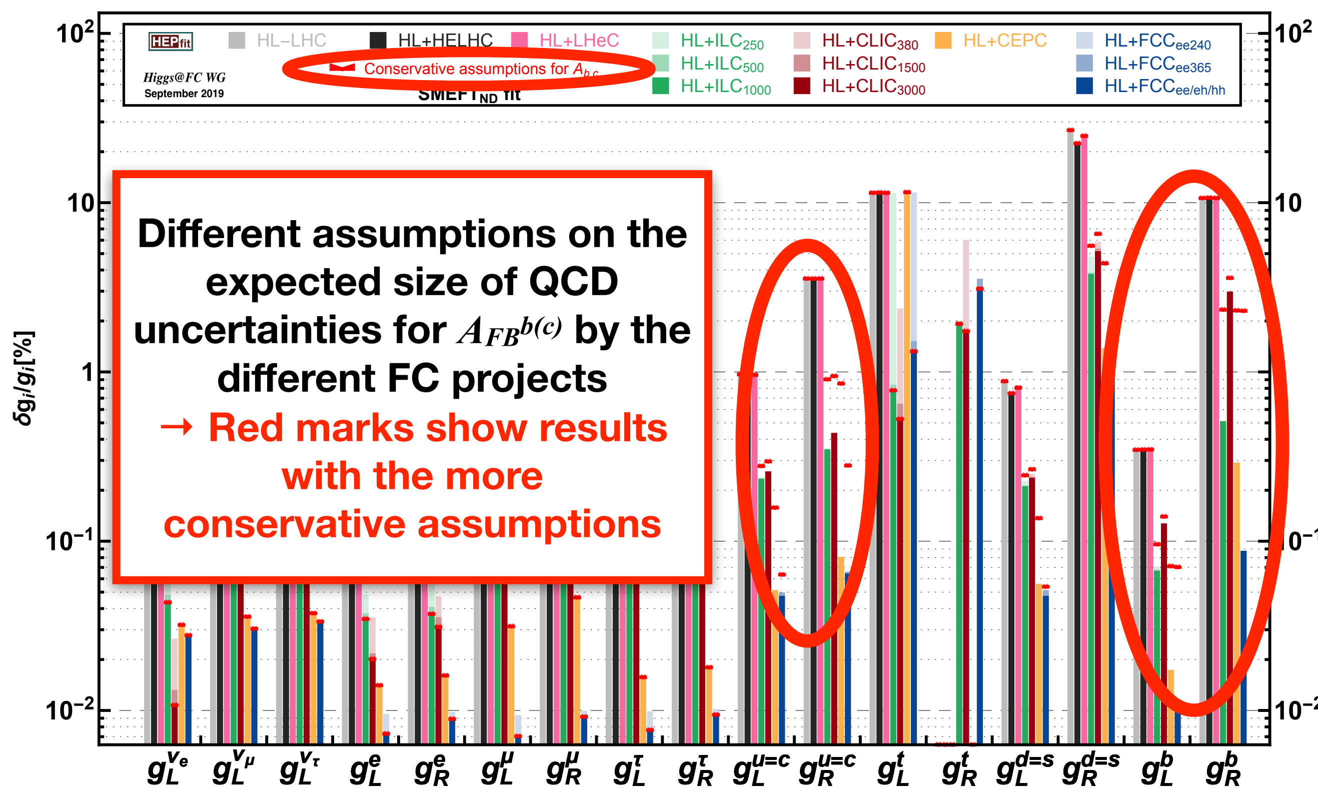




Need to study the impact on all directions in the SMEFT fits

Electroweak precision observables at the Z-pole

- ***EWPO*** at FC (in general) systematics dominated $\Rightarrow$ Projections for future sensitivity to BSM deformations depends on ***assumptions for such systematics***
- Several places where **clarifications/consensus are needed**:
  - Hadronic forward-backward asymmetries



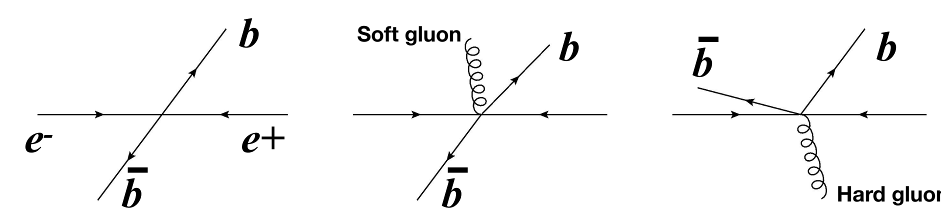
CC: From A_{FB} + $A_e(P_T)$

$$\left.\frac{A_b}{A_b^{SM}}\right|_{FCC_{ee}} \sim 0.003 \qquad \left.\frac{A_b}{A_b^{SM}}\right|_{CEPC} \sim 0.001$$

LC (with pol.): From $A_{FB,\,LR}$

$$\left.\frac{A_b}{A_b^{SM}}\right|_{ILC_{GigaZ}} \sim 0.0005 \qquad \left.\frac{A_b}{A_b^{SM}}\right|_{CLIC_{GigaZ}} \sim 0.001$$

QCD sys: jet direction vs quark direction



Systematics associated to this effect?

- Other examples: leptonic forward-backward asymmetries:

$$\left.\frac{\delta A_{FB}^{\mu}}{A_{FB}^{\mu,SM}}\right|_{FCC-ee} \sim 5.4\times 10^{-4} \qquad \left.\frac{\delta A_{FB}^{\mu}}{A_{FB}^{\mu,SM}}\right|_{CEPC} \sim 4.6\times 10^{-3}$$

Order of magnitude difference!

Electroweak precision observables at the Z-pole

- EW factories also offer **opportunities for flavor measurements**:
  - ✓ Tera Z: ~10^{12} Z decays into bb to test rare b-hadron decays, 10^{11} τ pairs for tests of LFV, limits on LFV decays of the Z,…

Order of magnitude estimates available, e.g., from CEPC CDR Vol. 2 (arXiv: 1811.10545 [hep-ex])

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\mathrm{BR}(B_s \to ee)$	2.8×10^{-7} (CDF) [438]	$\sim 7 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \mu\mu)$	0.7×10^{-9} (LHCb) [437]	$\sim 1.6 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \tau\tau)$	5.2×10^{-3} (LHCb) [441]	$\sim 5 \times 10^{-4}$ (LHCb) [435]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim 10\%$ (LHCb) [443, 444]	~few% (LHCb/Belle II) [435, 442]	~few %
$\mathrm{BR}(B \to K^*\tau\tau)$	–	$\sim 10^{-5}$ (Belle II) [442]	$\sim 10^{-8}$
$\mathrm{BR}(B \to K^*\nu\nu)$	4.0×10^{-5} (Belle) [449]	$\sim 10^{-6}$ (Belle II) [442]	$\sim 10^{-6}$
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	1.0×10^{-3} (LEP) [452]	–	$\sim 10^{-6}$
$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar) [475]	$\sim 10^{-9}$ (Belle II) [442]	$\sim 10^{-9}$
$\mathrm{BR}(\tau \to 3\mu)$	2.1×10^{-8} (Belle) [476]	$\sim$ few $\times 10^{-10}$ (Belle II) [442]	$\sim$ few $\times 10^{-10}$
$\frac{\mathrm{BR}(\tau\to\mu\nu\bar{\nu})}{\mathrm{BR}(\tau\to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [464]	$\sim 10^{-3}$ (Belle II) [442]	$\sim 10^{-4}$
$\mathrm{BR}(Z \to \mu e)$	7.5×10^{-7} (ATLAS) [471]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP) [469]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
$\mathrm{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LEP) [470]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

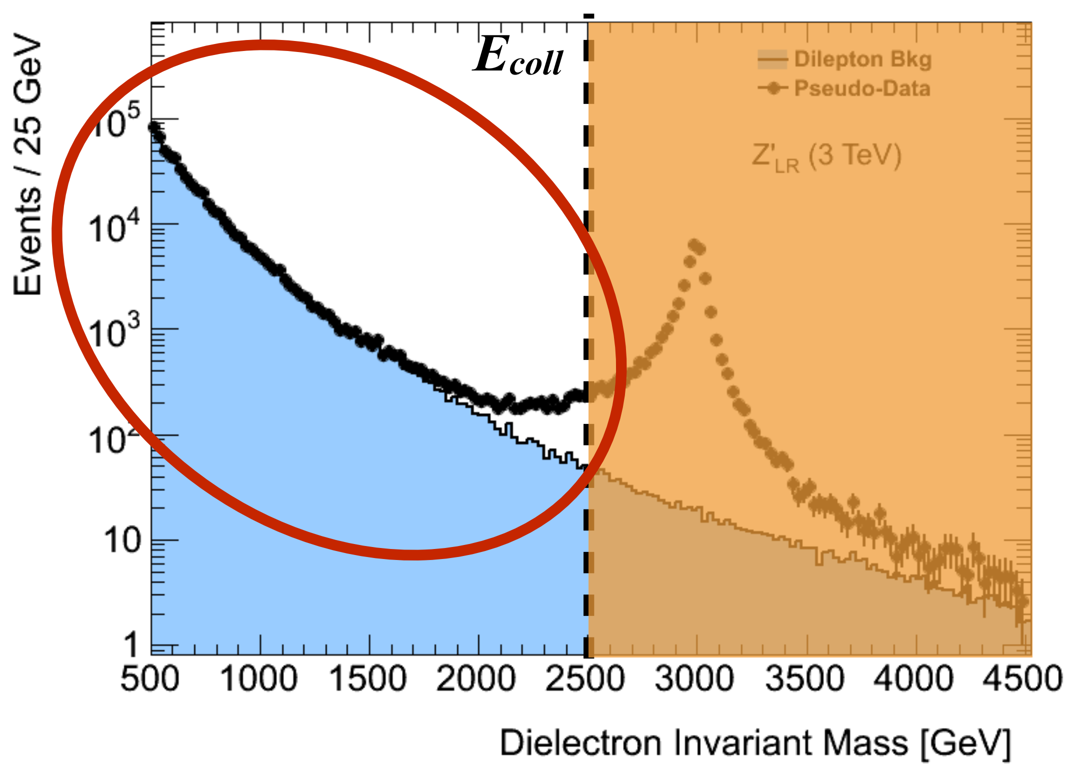
  - ✓ Sensitivity at Giga Z?

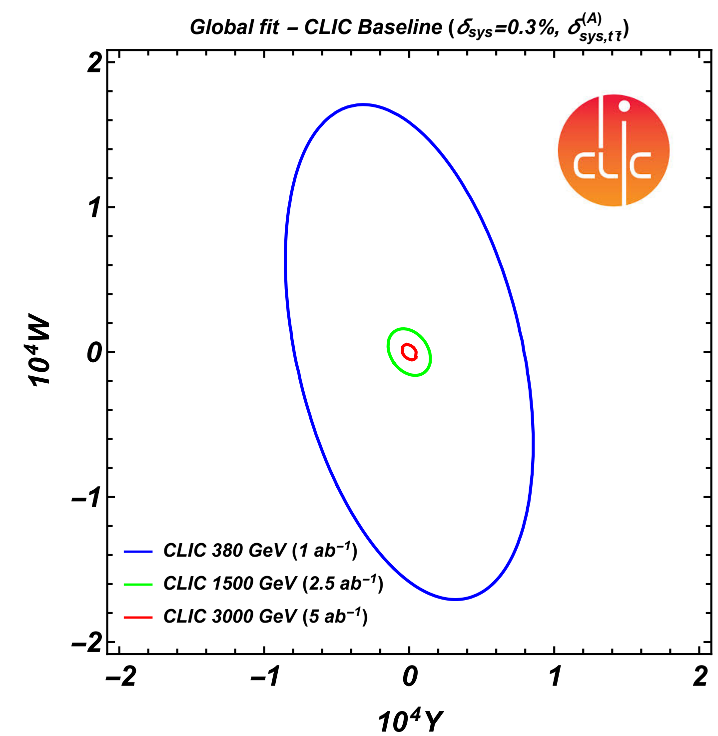
- EW measurements at **hadrons colliders**. Inputs for ESU studies limited to W mass and effective angle at HL-LHC:
  - ✓ HL-LHC: Γ_W?
  - ✓ Tests of lepton universality: Current LHC measurements of $W\to l_1\,\nu/W\to l_2\,\nu$ competitive (or even better) than LEP2. What is the ultimate precision at the end of LHC era? Projections at high-E pp colliders?

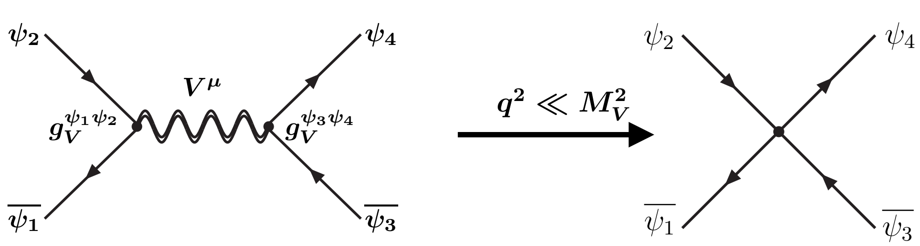
Electroweak measurements above the Z-pole

- EW measurements of $e^+e^-\to ff$ at high-E sensitive to different effects than Z-pole data. SMEFT picture:

  4 fermion operators ⇒ effects suppressed at Z-resonance but grow with E!







$$\frac{\Delta O}{O_{\rm SM}} \sim \frac{E^2}{\Lambda^2}$$

Universal NP

W **&** Y **parameters**

CLIC~25x better than HL-LHC
Similar to 100 TeV FCC-hh

- **ESU 2020:** This type of effects only studied for the particular case of oblique new physics (W & Y pars). Results available for CLIC and ILC. We estimated them for FCCee and CEPC

Electroweak measurements above the Z-pole

- **Snowmass 2021:** Can we also constrain all possible 4-fermion structures when departing from the oblique assumptions?

Better at the Z-pole

$\psi^2\varphi^2 D$	
$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$

Better at high-E

$(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$

$(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$

$(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$

- Complementarity Circular/Linear Colliders: Use Z-pole measurements to keep Zff corrections under control/Benefit from high-E to constrain 4-fermion effects.

- Interplay with low-energy precision experiments? e.g. atomic parity violation

Current APV measurement in Cs

$$Q_W({}^{133}_{78}\mathrm{Cs}) = -72.82 \pm 0.26_{\,\mathrm{exp.}} \pm 0.33_{\,\mathrm{th.}}$$

0.6% precision

Precise probe of lq contact interactions

Complementarity with the "Rare processes and precision measurements" Frontier (in particular RF3)

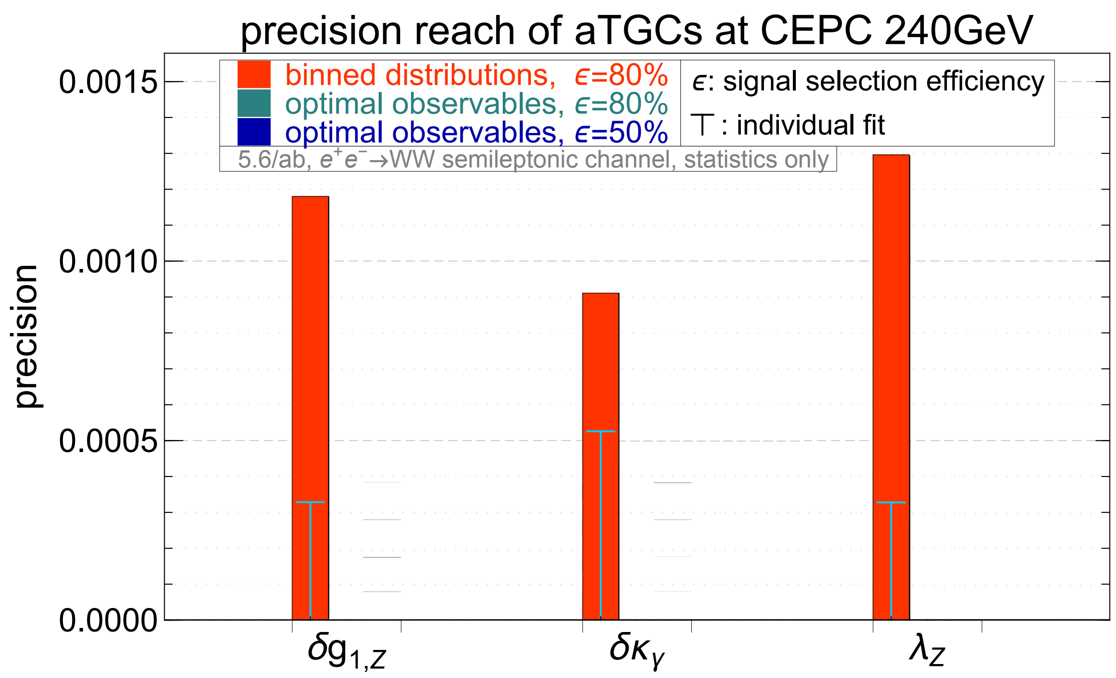
EW Physics at Snowmass 2021

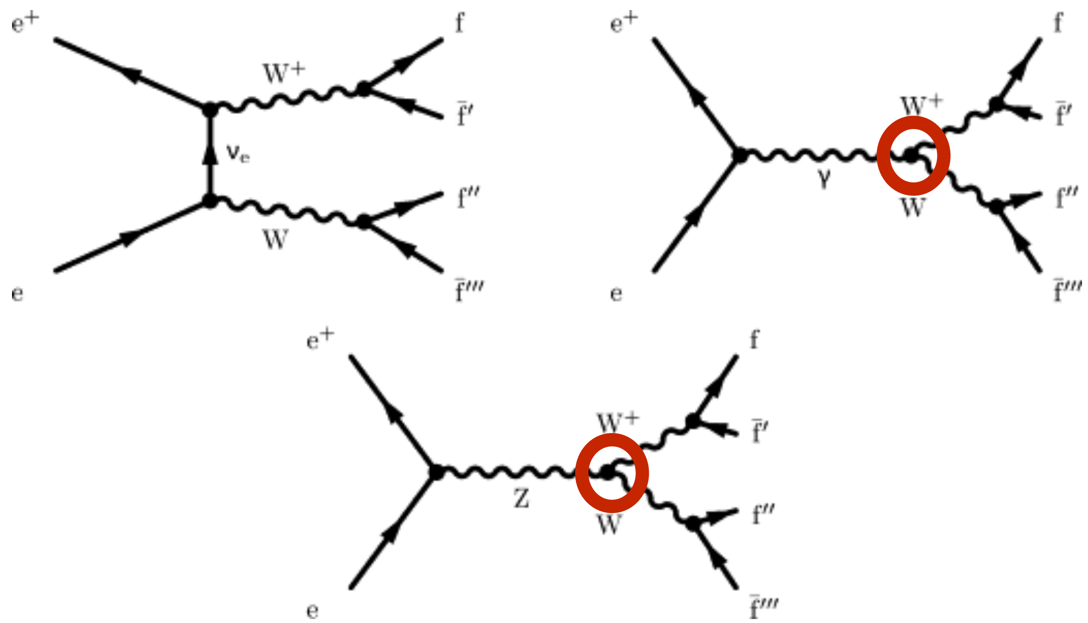
Multi-Boson processes

Electroweak measurements: Multi-boson production

W^+W^- production at future lepton colliders

- **EFT studies:** Current projections based on sensitivity to aTGC ONLY in differential angular distributions (ignoring correlations between bins)





J.B., G. Durieux, C. Grojean, J. Gu and A. Paul, *JHEP12 (2019) 117 (arXiv:1907.04311 [hep-ph])*

Electroweak measurements: Multi-boson production

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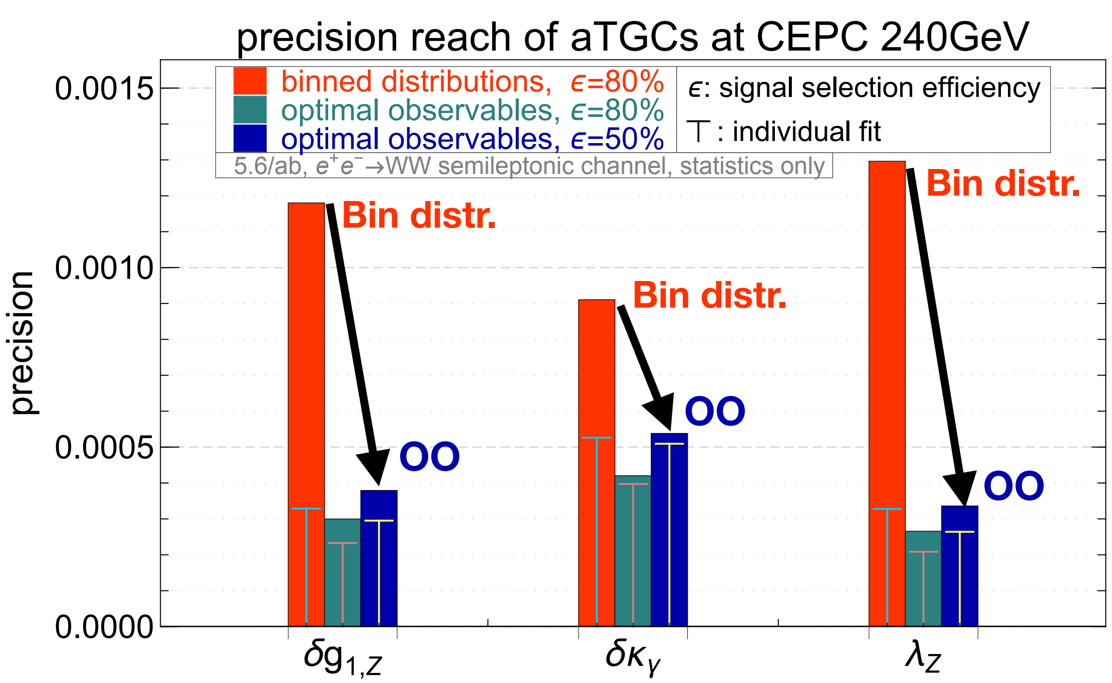
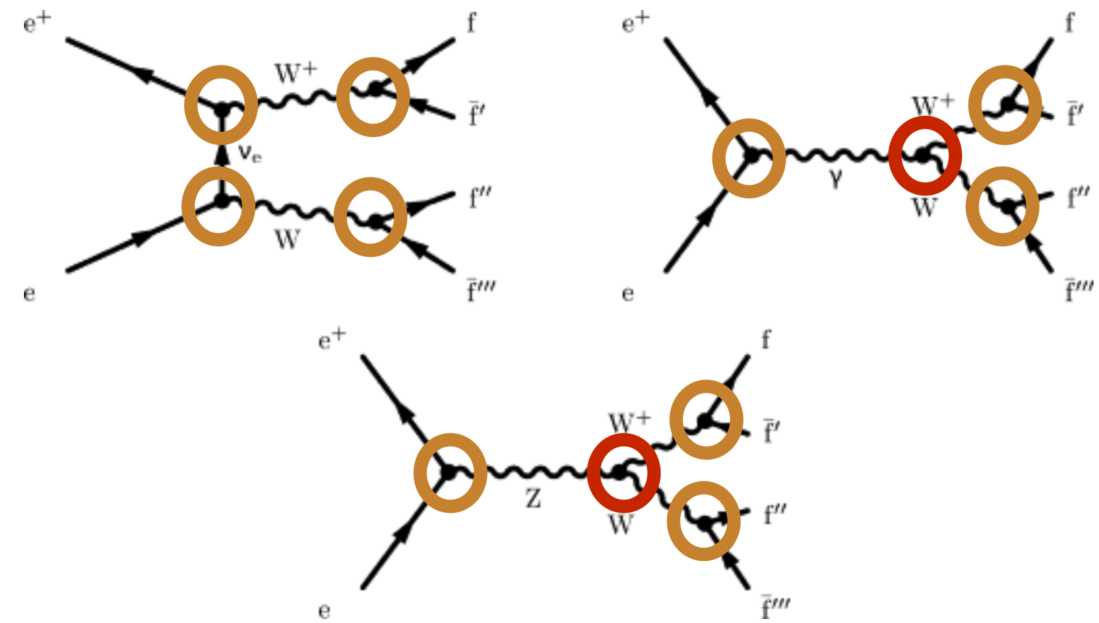


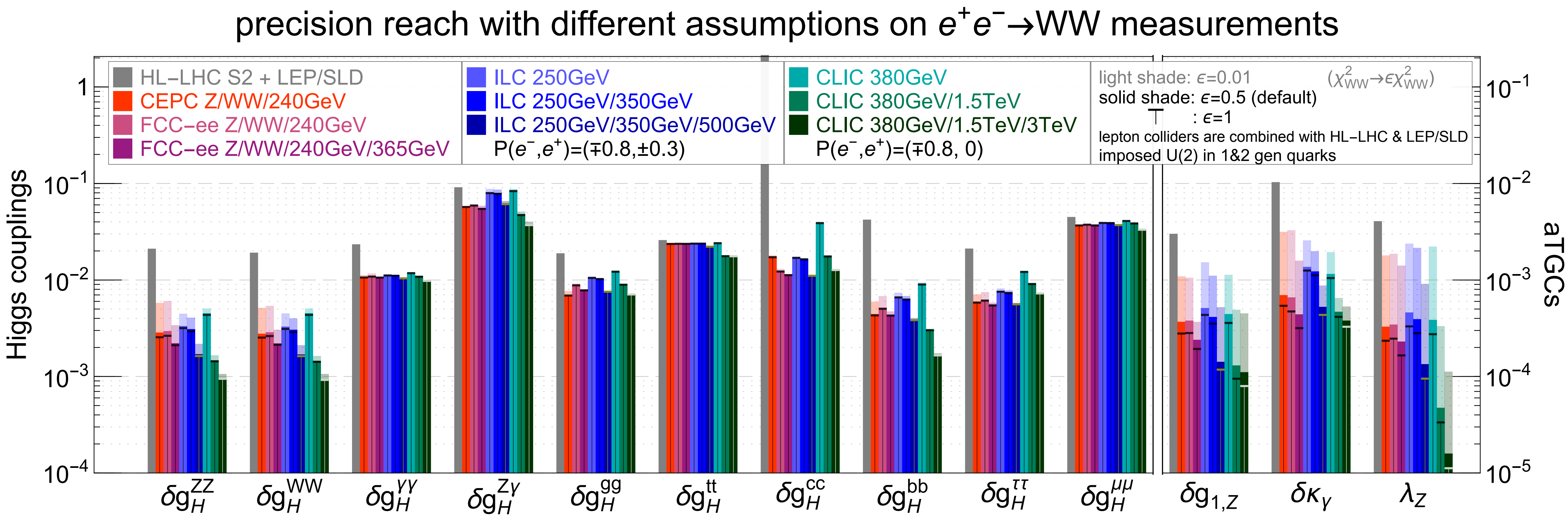


J.B., G. Durieux, C. Grojean, J. Gu and A. Paul, *JHEP12 (2019) 117 (arXiv:1907.04311 [hep-ph])*

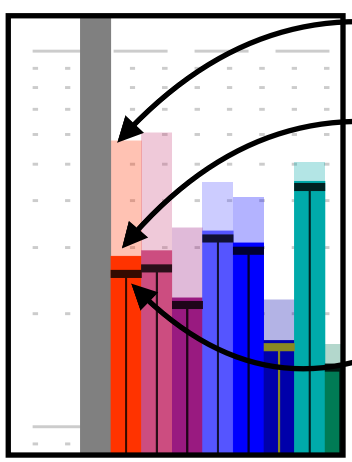
- In *JHEP12 (2019) 117* we prepared a new sensitivity study using full info about each event in the formalism of "optimal statistical observables" (OO):
  - ✓ We consider all possible BSM deformations within the dim-6 SMEFT framework
  - ✓ Default method only accounts for statistical sensitivity
    ⇒ Compensate omission of systematics via conservative selection efficiency **ε**

Electroweak measurements: Multi-boson production

EFT Higgs couplings and aTGC: dependence on $e^+e^-\to W^+W^-$ projections



J.B., G. Durieux, C. Grojean, J. Gu and A. Paul, JHEP12 (2019) 117 (arXiv:1907.04311 [hep-ph])



1% Efficiency in *ee→WW*

50% Efficiency in *ee→WW*

100% Efficiency in *ee→WW*

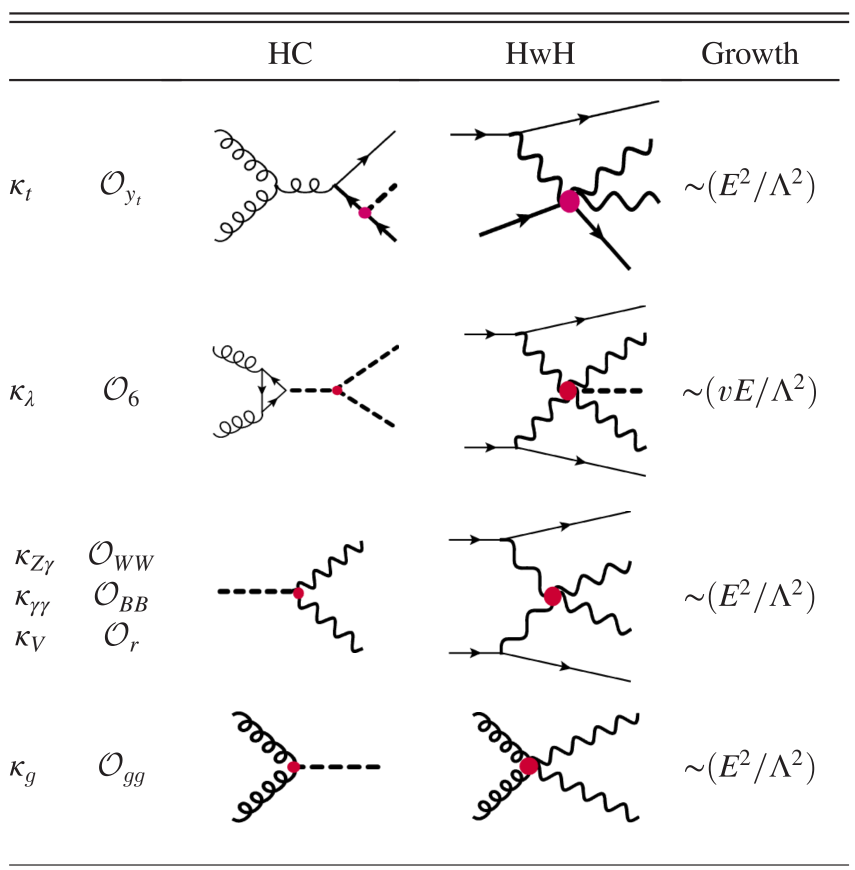
Influence of the assumptions in the ***OO*** study of ***WW*** production in the extraction of ***H*** couplings & aTGC

What is the potential of the method in presence of "realistic" systematics (EXP/TH)?

Electroweak measurements: Multi-boson production

- Multi-boson processes, *E*-growth and Higgs couplings:

B. Henning, D. Lombardo, M. Riembau, F. Riva, PRL 123, 181801 (2019) (arXiv:1812.09299 [hep-ph])



Multi-V probes of *E*-enhanced Higgs operators at hadron (lepton) colliders

$$\kappa_t:\ pp \to jt + V_L V_L',\quad (e^+e^- \to ll + \{tbW_L, tbZ_L, ttW_L, ttZ_L\}),$$

$$\kappa_\lambda:\ pp \to jjh + V_L V_L',\qquad (e^+e^- \to llhV_L V_L'),$$

$$pp \to jj + 4V_L,\qquad (e^+e^- \to ll4V_L),$$

$$\kappa_{\gamma\gamma,Z\gamma}:\ pp \to jj + V'V,\qquad (e^+e^- \to llV'V),$$

$$\kappa_V:\ pp \to jj + V_L V_L',\qquad (e^+e^- \to llV_L V_L'),$$

$$\kappa_g:\ pp \to W_L^+ W_L^-, Z_L Z_L,\qquad (e^+e^- \to lljj),$$

- In general, multi-boson processes (including VBS) not included in ESU 2020 studies. What is the potential of this type of complementary probes of *h* couplings?
  - ✓ Some studies available in CLIC YRs (*arXiv: 1812.02093[hep-ph]*).
  - ✓ See also *A. Costantini et al. arXiv: 2005.10289 [hep-ph]* for VBF/VBS at muon colliders
- Include also differential info in *WZ, Wh, WW,…* at 100 TeV hadron colliders. See, e.g., recent study of Wh in *F. Bishara et al., JHEP 07 (2020) 075 (arXiv: 2004.06122 [hep-ph].*

EW Physics at Snowmass 2021

Interplay with other frontiers

Interplay between EW/Higgs/Top

- ESU 2020 studies used simplified assumptions to study the Top Sector, ignoring:

Dipole ops.

$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\,\tilde{\varphi}W^I_{\mu\nu} + h.c.,$$
$$O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\,\tilde{\varphi}B_{\mu\nu} + h.c.,$$
$$O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\,\tilde{\varphi}G^A_{\mu\nu} + h.c..$$

4-fermion

$$O^1_{lq} \equiv \tfrac{1}{2}\,\bar{q}\gamma_\mu q\;\;\bar{l}\gamma^\mu l,$$
$$O^3_{lq} \equiv \tfrac{1}{2}\,\bar{q}\tau^I\gamma_\mu q\;\bar{l}\tau^I\gamma^\mu l,$$
$$O_{lu} \equiv \tfrac{1}{2}\,\bar{u}\gamma_\mu u\;\;\bar{l}\gamma^\mu l,$$
$$O_{ld} \equiv \tfrac{1}{2}\,\bar{d}\gamma_\mu d\;\;\bar{l}\gamma^\mu l,$$
$$O_{eq} \equiv \tfrac{1}{2}\,\bar{q}\gamma_\mu q\;\;\bar{e}\gamma^\mu e,$$
$$O_{eu} \equiv \tfrac{1}{2}\,\bar{u}\gamma_\mu u\;\;\bar{e}\gamma^\mu e,$$

Contribute to

***tt*, *tth*, *ttV* processes**

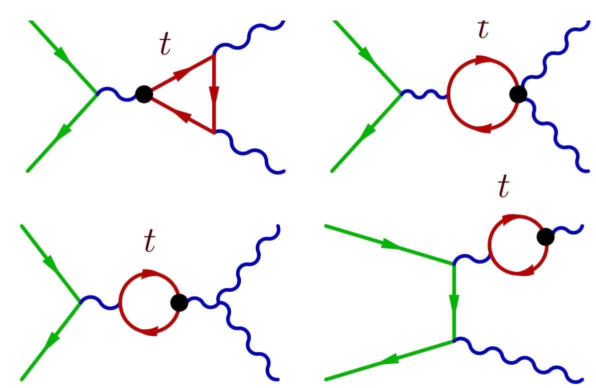
- A task for the Snowmass 2021 studies should be to incorporate these effects, and study in a precise way the interplay between the EW/Higgs/Top measurements. For instance:

  ✓ At NLO Top effects can generate sizable effects in EW/Higgs data:

e.g. Top couplings in $e^+e^-\to W^+W^-$

E. Vryonidou, C. Zhang,
JHEP 08 (2018) 036 (arXiv:1804.09766 [hep-ph])

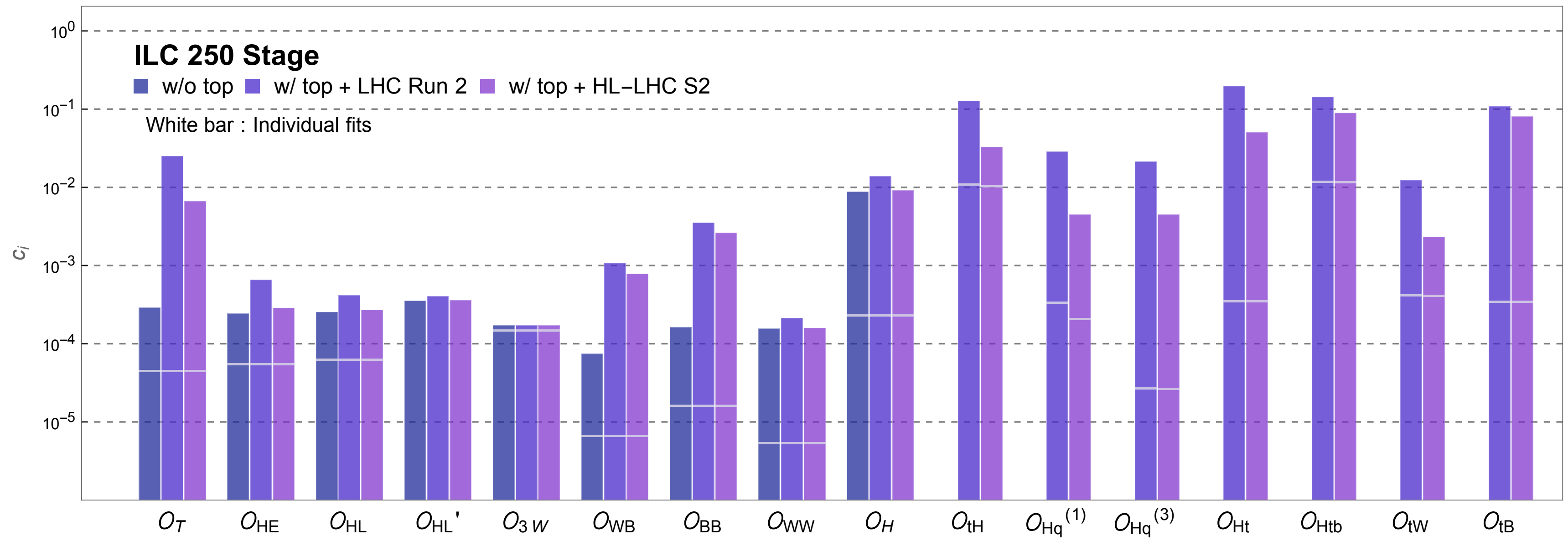
G. Durieux, J. Gu, E. Vryonidou, C. Zhang,
Chin. Phys. C42 (2018) 123107 (arXiv:1809.03520 [hep-ph])



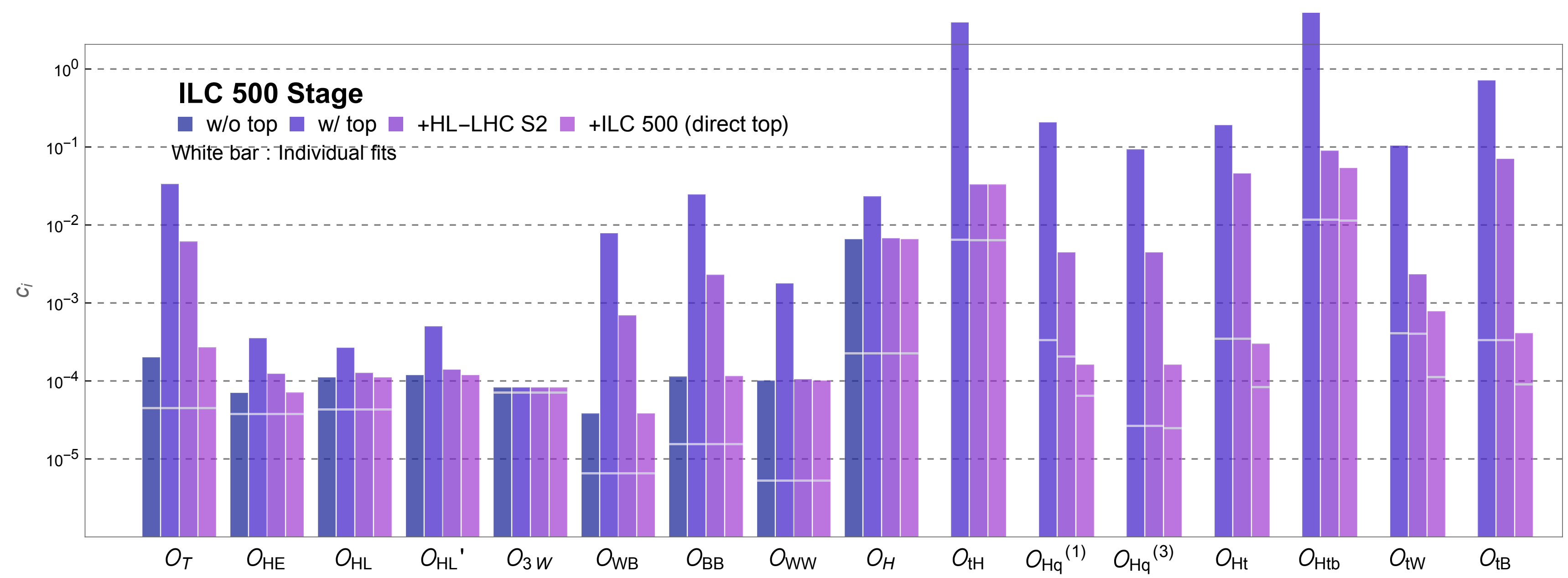
  ✓ Similar to what has been done to obtain indirect sensitivity to Higgs trilinear using single-H processes, these NLO effects can be used to obtain info from the Top below threshold ⇒ Complementary probe to effects in direct *tt* production

Interplay between EW/Higgs/Top

- NLO Top effects can generate sizable effects in EW/H data, providing indirect sensitivity:



ILC250: Sensitivity to Top ops. via RGE only



ILC250 +500: Adding tt production

S. Jung, J. Lee, M. Perelló, J. Tian, M. Vos, arXiv:2006.14631 [hep-ph]

Restricted to Top operators involving also H.

What is required to close a fully global EFT analysis?

What can be achieved at Circular Colliders? Complementarity?

See also

G. Durieux et al., JHEP 12 (2019) 098 (arXiv:1907.10619 [hep-ph]

Questions on the theory assumptions

Relevant for BSM interpretations/frontiers

- What is the impact of the theory assumptions made in the ESU2020 studies:

✓ Impact of NLO corrections: for recent studies, see e.g.

C. Hartmann, M. Trott,
Phys.Rev.Lett. 115 (2015) 19, 191801, arXiv:1507.03568 [hep-ph]
C. Hartmann, W. Shepherd, M. Trott,
JHEP 03 (2017) 060, arXiv:1611.09879 [hep-ph]

S. Dawson, P.P. Giardino,
Phys.Rev.D 97 (2018) 9, 093003, arXiv:1801.01136 [hep-ph]
Phys.Rev.D 98 (2018) 9, 095005, arXiv:1807.11504 [hep-ph]
Phys.Rev.D 101 (2020) 1, 013001, arXiv:1909.02000 [hep-ph]

- In general, ~O(10%) modifications if constrained at tree level
- Gives access to more operators/effects
- But also open flat directions ⇒ Need more observables to close a global fit

✓ Impact of (dim 6)^2, dim 8, … terms:

- More relevant in E-enchanced effects? (ILC 1 TeV, CLIC 3TeV)
- Validity of EFT description
- Gives access to more effects, e.g. RH CC in W processes

Questions on the theory assumptions

Relevant for BSM interpretations/frontiers

- What is the impact of the theory assumptions made in the ESU2020 studies:
  - ✓ Flavour assumptions: ESU2020 assumed neutral diagonal non-universal flavor assumptions:

$$\left[Y_f Y_f^\dagger, C_{\phi f}\right] = 0, \quad \left[Y_f^\dagger Y_f, C_{\phi f}^{(1),(3)}\right] = 0, \quad \left[Y_f, C_{f\phi}\right] = 0, \quad \ldots$$

where, e.g.

$$\mathcal{O}_{\phi u} = \left(\phi^\dagger i D_\mu \phi\right) \overline{u}_R \gamma^\mu u_R$$
$$\mathcal{O}_{d\phi} = \left(\phi^\dagger \phi\right) \overline{q}_L \phi d_R$$

> Alignment pattern rather contrived from BSM point of view/interpretation
> ⇒ Relax + combine with flavor projections?
>
> ⇒ How far can we go away from fermion universality w/o the above conditions?

- Is the SMEFT formalism the right approach? → Higgs/EW Effective Field Theory (HEFT)
  - ✓ More general structure of couplings (non-linear EWSB breaks TH correlations)
  - ✓ Cut-off $O(4\pi v)$~3 TeV
  - ✓ How far can we go in constraining the HEFT?
  - ✓ To what extent we can test which one is the right eff. description of EWSB?

Summary

- The European Strategy Update 2020 EW/Higgs studies provided a solid first step towards comparing the capabilities (and complementarities) of the different future collider projects in the Energy frontier in a realistic way.

- These studies were nevertheless limited in their nature by the official inputs available from the different FC groups, as well as by the TH assumptions needed for a coherent comparison of the different machines.

- These limitations provide a stepping stone for more complete studies to be done within the Snowmass 2021 process:
  - ✓ In this talk I reviewed a few points for improvement wrt. ESU2020, from the point of view of EW physics.
  - ✓ Much more can be done! (See also talk by C. Grojean at EF01 kickoff meeting for extended list covering also Higgs topics.)

- Clean separation between frontiers (EW, Higgs, Top, …), while useful, is not completely possible from the point of view of assessing the sensitivity to general BSM effects. Interaction between them is needed to obtain a global picture of the capabilities of future colliders!